Maximizing Revenue from Electrical Energy Storage in MISO Energy & Frequency Regulation Markets

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***Abstract*—FERC Order 755 requires RTO/ISOs to compensate the frequency regulation resources based on the actual regulation service provided. Based on this rule, a resource is compensated by a performance-based payment including a capacity payment which accounts for its provided regulation capacity and a performance payment which reflects the quantity and accuracy of its regulation service. The RTO/ISOs have been implementing different market rules to comply with FERC Order 755. This paper focuses on the MISO's implementation and presents the calculations to maximize the potential revenue of electrical energy storage (EES) from participation in arbitrage and frequency regulation in the day-ahead market using linear programming. A case study was conducted for the Indianapolis Power & Light's 20MW/20MWh EES at Harding Street Generation Station based on MISO historical data from 2014 and 2015. The results showed the maximum revenue was primarily produced by frequency regulation.**

***Index Terms*—FERC Order 755, frequency regulation market, energy arbitrage, electrical energy storage, capacity payment, performance-based payment, optimization, linear programming.**

I. Introduction

In the recent years, with the improvement in energy storage and power electronics technologies and the changes in the electricity marketplace, there has been a growing opportunity for grid-scale energy storage to provide services to the grid [1]. The cost-effective deployment of current electrical energy storage (EES) technologies depends on two main factors: 1) Policy and regulation that enable energy storage to resolve grid problems; 2) How energy storage might provide value in the current electricity markets [2].

In 2007 the Federal Energy Regulatory Commission (FERC) issued Order 890 to ensure the fair and equitable participation of non-generation resources in the markets [3]. To comply with this rule, the ISOs enhanced their market tariffs to allow demand response as well as energy storage resources to bid in their energy and ancillary services markets. Under these market rules, energy storage could generate revenue streams from energy arbitrage and participation in frequency regulation market. Arbitrage is the practice of buying energy during times of low demand when energy prices are low and selling energy during times of peak demand when energy prices are high. Frequency regulation service involves the increase (regulation up) or reduction (regulation down) of active power generation to the power grid to maintain the system frequency. Ancillary services can be provided by different market participants from generators to customers under demand response programs. In [4], battery energy storage (BESS) is proved a reliable source for primary frequency reserve. In [5], the BESSs play an important role in demand response (DR) programs to provide frequency regulation services. A comprehensive review of EES benefits is presented in [1].

In 2011 FERC issued Order 755 [6] which requires RTOs/ISOs to compensate the frequency regulation resources based on the actual regulation service provided. Based on this rule, a resource is compensated by a performance-based payment including a capacity payment which accounts for its provided regulation capacity and a performance payment which reflects the quantity and accuracy of its regulation service. The RTO/ISOs have been implementing different changes to their market rules to comply with FERC Order 755. These changes involve the modifications in the market clearing processes and the introductions of performance tests and performance-based payments.

This paper focuses on the MISO's implementation and presents the calculations to maximize the potential revenue of electrical energy storage participating in the MISO day-ahead market for energy and frequency regulation. The approach requires historical data of day-ahead energy and reserve market prices. In this approach, the revenue maximizations are formulated as linear programming problems in which the constraints are based on the energy storage model presented in [7]. The results provide the maximum revenue in the best-case scenario (with perfect knowledge of price data) that can be used to score other trading strategies. This approach is only valid for scenarios where the size of the storage is such that it does not impact market prices. For large systems that might impact the market, a production cost modeling approach must be implemented.

A similar approach has been used in the previous studies to investigate maximum revenue of an EES in CAISO [7], ERCOT [8] and PJM [9]. This paper extends the approach to include two-part performance-based payment as implemented in MISO. A case study was conducted for the Indianapolis Power & Light's 20MW/20MWh EES at Harding Street Generation Station based on MISO historical data from 2014 and

2015.

II. MISO Performance-based Compensation

In order to comply with FERC Order 755 [6], in December 2012 MISO began performance-based compensation for frequency regulation services [10]. MISO enhanced its market rules to provide two-part regulation payment to frequency regulation resources. Specifically, under MISO's market rules a regulation resource is required to submit a two-part regulation offer which include two components [11]:

1) Regulation capacity offer O_t^{RegC}[\$/MWh] represents the opportunity cost to hold capacity in reserve for frequency regulation.
2) Regulation mileage offer O_t^{RegM}[\$/MW] reflects the cost of movement to follow AGC regulation signals

The combined offer O_t^{Reg}[\$/MWh] which is used in market clearing process is specified as follows:

$$O_t^{\text{Reg}} = O_t^{\text{RegC}} + \alpha O_t^{\text{RegM}} \tag{1}$$

in which α is the mileage-to-capacity ratio. Based on historical data, MISO uses an average market-wide value $\alpha = 0.6/5min$ (or $7.2/h$) [10]. The combined offer O_t^{Reg}[\$/MWh] is the total cost for a resource to reserve 1MWh of capacity and to move αMW of mileage in an hour.

After the market (day-ahead or real-time) is cleared, MISO uses the regulation market clearing price $\text{MCP}_t^{\text{REG}}$ [\$/MWh] to pay a resource for its cleared regulation capacity q_t^{REG} [MWh]. This payment of $q_t^{\text{REG}}\text{MCP}_t^{\text{REG}}$ [\$] covers the capacity payment for q_t^{REG} [MWh] of capacity reserve and the mileage payment for αq_t^{REG} [MW] during hour t.

In order to evaluate a resource's performance, the following quantities are defined for each 5-min interval i based on MISO's AGC stepped set point s and the resource's actual response q at each 4-second step:

- Instructed mileage [MW]:
$$q_i^{\text{insM}} = \sum_{k=1}^{N} |s_k - s_{k-1}| \tag{2}$$
in which $N = 75$ is the number of stepped signals in 5-min interval.
- Desired mileage [MW]:
$$q_i^{\text{desM}} = \sum_{k=1}^{N} |d_k - d_{k-1}| \tag{3}$$
in which d_k is the desired plant output. The initial desired output d_0 at the beginning of each 5-min dispatch interval is the actual output. At each subsequent sample, the desired plant output ramps towards the AGC stepped set point.
- Target mileage [MW]:
$$q_i^{\text{tagM}} = \min\{q_i^{\text{insM}}, q_i^{\text{desM}}\} \tag{4}$$
- Actual mileage [MW]:
$$q_i^{\text{actM}} = \sum_{k=1}^{N} (|s_{k-1} - q_{k-1}| - |s_{k-1} - q_k|) \tag{5}$$
- Performance test for interval i:
$$\eta_i = \frac{q_i^{\text{actM}}}{q_i^{\text{desM}}} \begin{cases} \geq 0.7 & \text{Pass} \\ < 0.7 & \text{Fail} \end{cases} \tag{6}$$
- Performance test for hour t:
$$\eta_t = \begin{cases} 0 \text{ (Fail)} & \eta_i < 0.7 \text{ for 4 consecutive intervals} \\ 1 \text{ (Pass)} & \text{otherwise} \end{cases} \tag{7}$$

The regulation compensation is then adjusted based on the resource's actual performance. MISO uses the regulation mileage market clearing price $\text{MCP}_t^{\text{MIL}}$[\$/MW], which is the highest mileage offer from all resources [11], to pay (or charge) the resource for its additional (or undeployed) mileage. The adjustment at interval i to the regulation compensation of hour t are calculated as follows:

- Payment for additional mileage when $q_i^{\text{tagM}} \geq \frac{\alpha}{12} q_t^{\text{REG}}$:
$$A_t^i = \begin{cases} \left(q_i^{\text{tagM}} - \frac{\alpha}{12} q_t^{\text{REG}}\right) \text{MCP}_t^{\text{MIL}} & \text{if } \eta_i \geq 0.7 \\ \eta_i \left(q_i^{\text{tagM}} - \frac{\alpha}{12} q_t^{\text{REG}}\right) \text{MCP}_t^{\text{MIL}} & \text{if } \eta_i < 0.7 \end{cases} \tag{8}$$
- Charge for undeployed mileage when $q_i^{\text{tagM}} < \frac{\alpha}{12} q_t^{\text{REG}}$:
$$U_t^i = \left(\frac{\alpha}{12} q_t^{\text{REG}} - q_i^{\text{tagM}}\right) \text{MCP}_t^{\text{MIL}} \tag{9}$$

The total regulation compensation of hour t after adjustment is specified as:

$$R_t^{\Sigma} = \eta_t \left[q_t^{\text{REG}} \text{MCP}_t^{\text{REG}} + \sum_{i=1}^{M} \left(A_t^i - U_t^i + W_t^i\right) \right] \tag{10}$$

in which W_t^i is the make-whole payment from MISO to compensate for the total profit loss in interval i due to the fact that the undeployed mileage is charged back at the mileage market clearing price $\text{MCP}_t^{\text{MIL}}$ which is higher than the mileage offer O_t^{RegM} of the resource; and $M = 12$ is the number of intervals in an hour.

Based on the deployment of 2013, the followings have been observed by MISO [10]:

- The resources pass the hourly performance test by 77% of the time on a monthly average basis.
- The payment for extra mileage and the charge for undeployed mileage on monthly average basis are very close to each other by updating α every month.
- The make-whole payment for undeployed mileage is a small percentage (approximately 3%) of the monthly regulation revenue.

The cumulative density function (CDF) of AGC variations can be estimated from the ACE historical data. Figure 1 shows a ramp rate of approximately 6% of nameplate per 4 seconds will track 99.9% of 2015 AGC 4-second variations. It indicates that an EES with very high ramp rate such as flywheel or battery system could pass the hourly performance test at a close-to-perfect rate. However, in practice the pass rate can be lower due to EES operation and maintenance constraints.

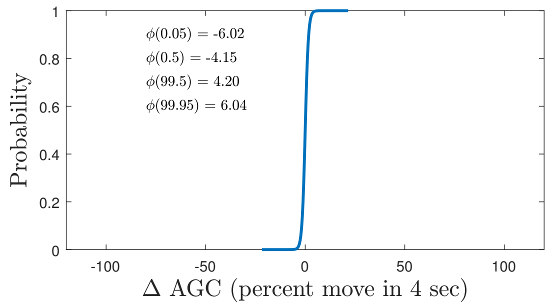

Fig. 1. Cumulative density function of 2015 AGC variation

Therefore, in this paper 95% pass rate is used and the monthly regulation compensation can be approximated as:

$$\sum_{t=1}^{T} R_t^{\Sigma} = 0.95 \times 1.03 \sum_{t=1}^{T} (q_t^{\text{REG}} \text{MCP}_t^{\text{REG}}) \tag{11}$$

III. Electrical Energy Storage (EES) Model

An EES system is generally characterized by the following parameters:

1) Power Rating [MW]: The maximum power that the EES can charge or discharge.
2) Energy Capacity [J or MWh]: The amount of energy that the EES can store.
3) Efficiency [%]: Efficiency can be broken into two components: conversion efficiency, γ_c, and storage efficiency, γ_s. The conversion efficiency represents the conversion losses encountered when energy is stored during charge and released during discharge. The storage efficiency describes the time-based losses in the EES system.
4) Ramp Rate [MW/min]: The ramp rate describes how quickly the EES can change its power level.

In this paper, the quantity of energy charged and discharged during each time period are analyzed. For arbitrage, the EES will maintain a constant output power over each time period. For regulation, it is assumed that the EES is capable of tracking the regulation signal at high ramp rate (i.e., the ramping time is negligible). If the ramp rate is slow compared to the time period, this approximation does not hold and a model that incorporates ramp rate must be employed.

The parameters involved in storage system constraints are shown in Table I. Thus, the maximum quantity that can be sold/discharged and bought/recharged in a single period τ are specified as follows:

$$\overline{q}^{\text{D}} = (\text{Maximum discharge power level}) \times \tau \tag{12}$$
$$\overline{q}^{\text{R}} = (\text{Maximum recharge power level}) \times \tau \tag{13}$$

For the EES that provides only energy arbitrage, there are two decision variables in the optimization: the energy sold (discharged) q_t^{D} and the energy purchased (recharged) q_t^{R} at time t, which are assumed to be non-negative. They are subjected to the following constraints :

$$0 \leq q_t^{\text{R}} \leq \overline{q}^{\text{R}}, \forall t \in T \tag{14}$$
$$0 \leq q_t^{\text{D}} \leq \overline{q}^{\text{D}}, \forall t \in T \tag{15}$$

TABLE I
Storage Parameters

Symbol	**Storage Parameter**
τ	Time period length (e.g., one hour)
T	Number of time periods in the optimization
$\overline{q}^{\text{D}}$	Maximum energy sold in a single period (MWh)
$\overline{q}^{\text{R}}$	Maximum energy bought in a single period (MWh)
$\overline{S}$	Maximum energy capacity (MWh)
γ_s	Storage efficiency over one period (%)
γ_c	Conversion efficiency (%)

In this case, the state of charge (SOC) S_t at any time t is given by:

$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^{\text{R}} - q_t^{\text{D}} \ \forall t \in T \tag{16}$$

which states that the SOC at time t is the SOC at time $t-1$ adjusted for storage plus any net charging (adjusted for conversion losses) minus the quantity discharged during t.

For the EES that is participating in energy arbitrage and frequency regulation market, an additional decision variable must be added to capture the quantity allocated to the regulation reserve, q_t^{REG}, which is assumed to be non-negative. This allocation to regulation reduces the maximum potential quantities allocated to arbitrage subjected to the charge/discharge constraints:

$$0 \leq q_t^{\text{R}} + q_t^{\text{REG}} \leq \overline{q}^{\text{R}}, \forall t \in T \tag{17}$$
$$0 \leq q_t^{\text{D}} + q_t^{\text{REG}} \leq \overline{q}^{\text{D}}, \forall t \in T \tag{18}$$

In regulation market, there is no guarantee that the capacity reserved will actually deployed. Therefore, it is useful to define the RegUp efficiency γ_t^{RU} and the RegDown efficiency γ_t^{RD} as the fraction of the reserve capacity which is actually deployed for RegUp/RegDown at time t. Thus, the SOC at time t of an EES participating in arbitrage and regulation is given by:

$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^{\text{R}} - q_t^{\text{D}} + \gamma_c \gamma_t^{\text{RD}} q_t^{\text{REG}} - \gamma_t^{\text{RU}} q_t^{\text{REG}}, \forall t \in T \tag{19}$$

In both cases, the SOC must be within its physical limits as described in the following constraint:

$$0 \leq S_t \leq \overline{S}, \forall t \in T \tag{20}$$

IV. Maximizing EES Revenue

In this paper, the problem of maximizing revenue from an EES is formulated as an LP optimization problem [12]. The objectives are to maximize the potential revenue of an EES in two different scenarios: arbitrage and arbitrage combined

TABLE II
NOMENCLATURES

Symbol	Description
P_t	LMP for energy at time t [\$/MWh]
C_d	Cost for discharging [\$/MWh]
C_r	Cost for recharging [\$/MWh]
q_t^D	Energy discharged at time t [MWh]
q_t^R	Energy charged at time t [MWh]
q_t^REG	Regulation capacity at time t [MWh]
$\mathrm{MCP}_t^\mathrm{REG}$	Regulation market clearing price at time t [MWh]
e^{-rt}	Discounting term (time value of money)

with participation in the regulation market. The constraints are enforced using the aforementioned EES model.

Specifically, the optimizations are formulated as follows where all the variables and parameters are defined in Table. II:

- Arbitrage:

$$\mathrm{Max} \sum_{t=1}^{T} \left[(\mathrm{P}_t - \mathrm{C}_\mathrm{d})\, q_t^\mathrm{D} - (\mathrm{P}_t + \mathrm{C}_\mathrm{r})\, q_t^\mathrm{R} \right] e^{-rt} \tag{21}$$

s.t. (14), (15) and (20).

- Arbitrage and regulation:

$$\mathrm{Max} \sum_{t=1}^{T} \Big[(\mathrm{P}_t - \mathrm{C}_\mathrm{d})\, q_t^\mathrm{D} - (\mathrm{P}_t + \mathrm{C}_\mathrm{r})\, q_t^\mathrm{R} + 0.95 \times 1.03 q_t^\mathrm{REG} \mathrm{MCP}_t^\mathrm{REG} \Big] e^{-rt} \tag{22}$$

s.t. (17), (18) and (20).

In many areas, the net energy for regulation is settled at the real-time price. This provides an additional arbitrage opportunity between the day ahead price and the real-time price. For this analysis, the price P_t was assumed to represents both. While this does not reflect the actual settlement process, it keeps the optimization from incorporating any arbitrage between the day ahead and the real-time market.

V. A Case Study

In this section, the maximum revenue for arbitrage and frequency regulation of the EES system located at Harding Street Generation Station of Indianapolis Power & Light is evaluated. The Harding Street EES is a 20MW/MWh Li-ion battery energy storage system (BESS) which can provide primary frequency response and other ancillary services such as energy arbitrage or frequency regulation [14].

The optimization problems in (21) and (22) were formulated using Pyomo optimization modeling language [13]. The following inputs were considered:

- MISO historical price data of 2014 and 2015 [15] were used.
- Hourly day-ahead prices for node IPL.16STOU6O6 were used.

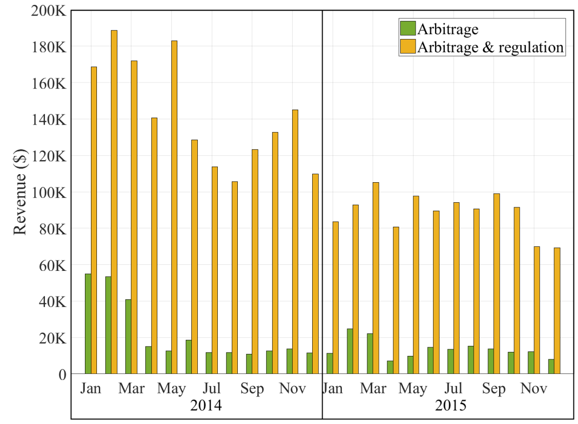

Fig. 2. Optimization Results

- Both RegUp and RegDown efficiencies are assumed to be 25%: $\gamma_t^\mathrm{RU} = \gamma_t^\mathrm{RD} = 0.25$.
- The system's efficiencies are approximated as: $\gamma_\mathrm{s} = 1$ and $\gamma_\mathrm{c} = 0.85$.
- The discharging and recharging cost were neglected: $C_\mathrm{d} = C_\mathrm{r} = 0$.
- The discount rate was neglected: $r = 0$.
- The SOC is maintained at 50% at the end of each day.

The monthly revenue of 2014 and 2015 in both scenarios using perfect knowledge are shown in Figure 2. The revenue from arbitrage combined with regulation service is shown much higher than from arbitrage only. Optimal results for arbitrage combined with regulation are show in Table III in which $\%q^\mathrm{R}$, $\%q^\mathrm{D}$ and $\%q^\mathrm{REG}$ respectively represent the time (percentage) each month for recharging, discharging and regulation; and R^arb, R^reg and R^tot are arbitrage, regulation and total revenue. The optimal policy in this case is to participate in regulation market the majority of the time while maintaining the SOC by arbitrage. Therefore, the majority of monthly revenue is from frequency regulation. The revenue from arbitrage is low and in many cases is negative due to the purchased energy to compensate for the losses while participating in frequency regulation. The regulation revenue is decreasing from 2014 to 2015 as a result of the decrease in energy price which reduces the opportunity cost for holding capacity reserve.

Without perfect knowledge of the prices, $D-1$ forecast method was used. In other words, price data of the prior day were used to determine trading policy for the current day. The results are as follows:

- Arbitrage only: the annual revenues were approximately 83.51% of 2014's and 81% of 2015's optimal revenues which were calculated with perfect knowledge.
- Arbitrage combined with regulation: the annual revenues were approximately 97.42% of 2014's and 97.34% of 2015's optimal revenues which were calculated with perfect knowledge. In this case, the deviations from optimal results are much smaller due to the small forecast error

TABLE III
ARBITRAGE AND REGULATION OPTIMIZATION RESULTS 2014-2015

Month	$\%q^{\mathbf{R}}$	$\%q^{\mathbf{D}}$	$\%q^{\mathbf{REG}}$	$R^{\mathbf{arb}}$	$R^{\mathbf{reg}}$	$R^{\mathbf{tot}}$
01/14	26.61	6.59	100	$7.28K	$161.40K	$168.67K
02/14	28.13	7.89	100	$8.57K	$180.13K	$188.69K
03/14	23.66	3.76	100	-$1.77K	$173.68K	$171.90K
04/14	16.25	1.25	100	-$15.14K	$155.76K	$140.62K
05/14	15.73	0.81	100	-$15.58K	$198.48K	$182.90K
06/14	22.92	2.36	100	-$6.76K	$135.39K	$128.63K
07/14	19.49	1.08	100	-$11.50K	$125.20K	$113.70K
08/14	20.03	1.08	100	-$12.56K	$118.11K	$105.56K
09/14	16.94	0.83	100	-$12.07K	$135.40K	$123.32K
10/14	13.44	0.54	100	-$14.66K	$147.30K	$132.64K
11/14	14.03	0.14	100	-$16.79K	$161.91K	$145.12K
12/14	19.22	1.61	100	-$12.73K	$122.61K	$109.88K
			Total	**-$103.72K**	**$1,815.36K**	**$1,711.64K**
01/15	19.22	2.42	100	-$11.68K	$95.19K	$83.52K
02/15	27.83	5.51	100	-$1.68K	$94.47K	$92.79K
03/15	25.67	4.17	100	-$3.55K	$108.68K	$105.13K
04/15	15.28	1.25	100	-$12.42K	$93.09K	$80.67K
05/15	20.70	1.75	100	-$10.54K	$108.17K	$97.63K
06/15	29.31	2.78	100	-$5.37K	$94.90K	$89.53K
07/15	25.67	2.02	100	-$7.70K	$101.78K	$94.08K
08/15	31.05	3.36	100	-$4.95K	$95.64K	$90.69K
09/15	25.83	2.36	100	-$6.58K	$105.57K	$99.00K
10/15	18.55	1.88	100	-$9.98K	$101.60K	$91.62K
11/15	22.78	3.33	100	-$8.65K	$78.68K	$70.03K
12/15	16.53	0.94	100	-$10.27K	$79.49K	$69.21K
			Total	**-$93.35K**	**$1157.27K**	**$1063.92K**

of reserve market prices.

VI. CONCLUSIONS

In this paper, MISO's market rules for performance-based regulation payment have been reviewed. A linear programming approach has been used to estimate the potential revenues of an EES system in two cases: arbitrage only and arbitrage combined with frequency regulation. The approach was extended to include MISO's performance-based regulation payment. With perfect knowledge of the price data, the approach finds the upper bounds for the potential revenues which can be used for evaluating other trading strategies. A case study was conducted for the Indianapolis Power & Light's 20MW/20MWh EES at Harding Street Generation Station based on MISO historical data from 2014 and 2015. The results showed the revenues were much higher when participating in regulation market. The optimal policy in this case is to participate in regulation market the majority of the time while maintaining the SOC by arbitrage. Without perfect knowledge of the prices, $D-1$ trading policy can capture as much as 83.51% of the arbitrage-only optimal revenue and 97.42% of the arbitrage-regulation optimal revenue. Future work would consider the uncertainties of the forecast data as well as include a more sophisticated model that distinguishes different energy storage technologies in the approach.

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